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An investigation of a super-Earth exoplanet with a greenhouse-gas atmosphere using a general circulation model

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ABSTRACT

We use the Massachusetts Institute of Technology general circulation model (GCM) dynamical core, in conjunction with a Newtonian relaxation scheme that relaxes to a gray, analytical solution of the radiative transfer equation, to simulate a tidally locked, synchronously orbiting super-Earth exoplanet. This hypothetical exoplanet is simulated under the following main assumptions: (1) the size, mass, and orbital characteristics of GJ 1214b (Charbonneau, D. [2009]. Nature 462, 891–894), (2) a greenhouse-gas dominated atmosphere, (3), the gas properties of water vapor, and (4) a surface. We have performed a parameter sweep over global mean surface pressure (0.1, 1, 10, and 100 bar) and global mean surface albedo (0.1, 0.4, and 0.7). Given assumption (1) above, the period of rotation of this exoplanet is 1.58 Earth-days, which we classify as the rapidly rotating regime. Our parameter sweep differs from Heng and Vogt (Heng, K., Vogt, S.S. [2011]. Mon. Not. R. Astron. Soc. 415, 2145–2157), who performed their study in the slowly rotating regime and using Held and Suarez (Held, I.M., Suarez, M.J. [1994]. Bull. Am. Meteorol. Soc. 75 (10), 1825–1830) thermal forcing. This type of thermal forcing is a prescribed function, not related to any radiative transfer, used to benchmark Earth's atmosphere. An equatorial, westerly, superrotating jet is a robust feature in our GCM results. This equatorial jet is westerly at all longitudes. At high latitudes, the flow is easterly. The zonal winds do show a change with global mean surface pressure. As global mean surface pressure increases, the speed of the equatorial jet decreases between 9 and 15 h local time (substellar point is located at 12 h local time). The latitudinal extent of the equatorial jet increases on the nightside. For the two greatest initial surface pressure cases, an increasingly westerly component of flow develops at middle to high latitudes between 11 and 18 h local time. On the nightside, the easterly flow in the midlatitudes also increases in speed as global mean surface pressure increases. Furthermore, the zonal wind speed in the equatorial and midlatitude jets decreases with increasing surface albedo. Also, the latitudinal width of the equatorial jet decreases as surface albedo increases.

1. Introduction

Infrared observations of transiting planets over the past decade have opened a window on a new regime of atmospheric dynamics (e.g., Knutson et al., 2007). The first transiting exoplanets discovered and modeled were "hot Jupiters", planets broadly similar in size to Jupiter that orbit their parent stars in close-in orbits (often with periods less than a few Earth-days) and hence receive an immense amount of stellar flux (Mayor and Queloz, 1995; Charbonneau et al., 2000). Their masses and radii suggest that their atmospheres are hydrogen-dominated (Fortney et al., 2007), similar to Solar System gas giants. They are also expected to be tidally locked and synchronously orbiting their parent star, always keeping one face to their parent star. These properties imply that their circulation patterns will be entirely unlike anything found in the Solar System.

1.1. Review of exoplanet general circulation models

Many exoplanet general circulation models (GCMs) have been developed, almost all from existing terrestrial GCMs. Showman and Guillot (2002) developed the first true 3-D GCM of an exoplanet (in this case hot Jupiters such as HD 209458b) using the Explicit Planetary Isentropic Coordinate (EPIC) model (Dowling et al., 1998). This model differed from previous models of brown dwarfs in that they included the intense irradiation received from their parent star and differed from previous exoplanet models in that they included the effects of advection. They predicted superrotating (westerly) winds, which later models have verified, and phase-curve offsets before the latter was discovered observationally. Cooper and Showman (2005) modeled HD 209458b using

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version 2 of the ARIES/GEOS dynamical core (Suarez and Takacs, 1995) with Newtonian relaxation to a prescribed equilibrium temperature. This model improved on Showman and Guillot (2002) by having a more realistic radiative-equilibrium temperature, better resolution, and a deeper domain. It was thus able to better predict the day–night temperature difference. Cooper and Showman (2006) then used the Cooper and Showman (2005) model to study the chemistry of HD 209458b. CO and CH_4 were represented as passive tracers. They found that where there is disequilibrium chemistry of CO and CH_4, their abundance also depends on the meteorology of the planet.

Several hot Jupiter models have used the equivalent barotropic formulation or shallow water version of the primitive equations of atmospheric fluids. Cho et al. (2003) developed a GCM for HD 209458b using the equivalent barotropic formulation of the shallow-water equations with Newtonian heating to a prescribed equilibrium state and obtained different results than Showman and Guillot (2002). Namely, they predicted a banded structure with three broad zonal jets and easterly flow at the equator. Menou et al. (2003), in a companion paper, generalized the Cho et al. (2003) GCM to other giant planets by varying the Rossby and Burger numbers. They found that close-in giant exoplanets lie in a different regime of flow patterns than Solar System gas giant planets. Namely, the former have few zonal jets, while the latter have many. Cho et al. (2008) extended the study of Cho et al. (2003) to a much larger parameter space by varying the initial RMS velocity, global mean temperature at cloud tops, thermal forcing amplitude, Rossby deformation radius at the pole, and nondimensional Rhines length at the equator. They concluded that giant exoplanets have a polar vortex that revolves around each pole, a low (two or three) number of zonal jets (in contrast with Solar System gas giants), and a temperature field that depends on the circulation. Rauscher et al. (2008) used the GCM of Cho et al. (2008) to predict observational signatures of hot Jupiters. Langton and Laughlin (2007) used a shallow water model similar to Cho et al. (2003) and found a cold spot centered 76° east of the antistellar point. They attributed this disagreement to a difference in their radiative time constant.

Meanwhile, hot Jupiter models with other types of dynamical cores continued to develop and improve. Showman et al. (2008) simulated the atmospheres of the hot Jupiters HD 209458b and HD 189733b using a GCM based on the Massachusetts Institute of Technology (MIT) GCM dynamical core, which uses the full 3-D privative equations. The Showman et al. (2008) GCM was radiatively forced using Newtonian relaxation to a radiative equilibrium state. Showman et al. (2009) continued this work using a radiative transfer (RT) scheme (Marley and McKay, 1999) that calculated the RT fluxes directly using a correlated-k scheme with multiple wavelengths in the two-stream approximation. Both of these studies showed flow from the substellar to antistellar point along the equator and over the poles at lower pressures, while a westerly equatorial jet and easterly polar flow developed at higher pressures. Menou and Rauscher (2009) used the Intermediate GCM dynamical core of Hoskins and Simmons (1975), which solves the primitive equations. This GCM was thermally forced by Newtonian relaxation to a prescribed equilibrium temperature and used to compare the barotropic (hot Jupiter) and baroclinic (Earth-like) regimes. Rauscher and Menou (2010) used the same model as Menou and Rauscher (2009) to check that hot Jupiters were being modeled consistently with the results of Cooper and Showman (2005, 2006) and Showman et al. (2008, 2009). Perna et al. (2010a) used the Rauscher and Menou (2010) GCM to show that magnetic drag is a plausible mechanism to limit wind speeds in hot Jupiters; Perna et al. (2010b) used the Rauscher and Menou (2010) GCM to show that Ohmic dissipation is a non-negligible heat source in hot Jupiters. The Menou and Rauscher (2009) GCM was subsequently improved by Rauscher and Menou (2012) to include dual band, double-gray RT.

Several studies have investigated the effects of particular aspects of hot Jupiter GCMs on the resulting circulation and temperature. Burkert et al. (2005) used an inviscid, primitive equation model in 2-D (varying in azimuth and radius) with flux limited radiative diffusion to show that the nightside temperature is sensitive to atmospheric opacity. Similarly, Dobbs-Dixon and Lin (2008) used a flux limited radiative inviscid hydrodynamical model (truncated at ±70° latitude) to show that atmospheres with large opacity have a large day–night temperature difference, while atmospheres with reduced opacity have a more uniform temperature. Dobbs-Dixon et al. (2010) improved on the model of Dobbs-Dixon and Lin (2008) by using decoupled radiative and thermal components with updated opacities. They also added viscosity, and found that high viscosity resulted in subsonic flow, while low viscosity produced supersonic flow. The addition of viscosity changed the circulation patterns and variability of flows. Langton and Laughlin (2008) used a shallow water model with two a two-wavelength radiative transfer to investigate the effect of high orbital eccentricity on hot Jupiters. They found that the atmospheric response was driven primarily by the intense irradiation at periastron and that the resulting expansion of heated air produced high velocity turbulent flow (with some planets developing superrotating acoustic fronts as well). Finally, Thrastarson and Cho (2010), using a GCM with the primitive equations and Newtonian relaxation to a prescribed equilibrium state, found that different initial states of the initial zonal jet (which had the most significant effect), thermal drag timescale, spectral truncation number, and superviscosity coefficient, lead to markedly different results for circulation and temperature. Thrastarson and Cho (2011), using the same GCM, found that a short Newtonian relaxation time led to large amounts of unphysical, gird-scale oscillations that contaminated the flow field.

Heng et al. (2011b) performed benchmark simulations of Earth, tidally locked synchronously orbiting Earth, a shallow hot Jupiter, and a deep HD 209458b. The purpose of benchmark simulations is to compare dynamical cores of GCMs to determine if differences are due to numerical modeling procedures or "higher level" physical parameterizations. Heng et al. (2011b) followed the standard Earth method of Held and Suarez (1994) with a slight modification to include the effects of a tidally locked synchronously orbiting planet. This scheme used Newtonian relaxation to relax to the following radiative equilibrium temperature:

$$T_{eq,hs} = \max\left\{T_{strat}, \left[T_{surf} - \Delta_h \cos(\lambda - 180^\circ)\cos\phi - \Delta_z \log\left(\frac{p}{p_o}\right)\cos^2\phi\right]\left(\frac{p}{p_s}\right)^{R/c_p}\right\}, \quad (1)$$

where $T_{eq,hs}$ is the Held and Suarez (1994) equilibrium temperature (in K), T_{strat} = 200 K is the stratospheric temperature, T_{surf} = 315 K is the surface temperature, Δ_h = 60 K is the equator to pole temperature difference, λ is longitude, ϕ is latitude, Δ_z = 10 K is a characteristic temperature difference in altitude, p is pressure, p_s is the surface pressure (here taken to be 10^5 Pa), R is the specific gas constant, and c_p is the specific heat at constant pressure. Since Held and Suarez (1994) were comparing terrestrial dynamical cores, they set their parameters in Eq. (1) to mimic the temperature distribution in Earth's atmosphere. Heng et al. (2011b), in their benchmark test, compared the Geophysical Fluid Dynamics Laboratory (GFDL)–Princeton flexible modeling system (FMS) (see references in Heng et al. (2011b)) spectral and finite difference cores. They found qualitative and quantitative agreement between the two cores in all but the deep HD 209458b case, where horizontal dissipation changed